ENVIRONMENTAL RESEARCH

MINISTRY OF ENVIRONMENT AND ENERGY

Ontario

ISBN 0-7778-4978-X

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FINAL REPORT

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FEBRUARY 1996

PIBS 3417E

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ACKNOWLEDGEMENT AND DISCLAIMER

This report was prepared for the Ontario Ministry of Environment and Energy as part of a Ministry funded project. The views expressed in this report are those of the author and do not necessarily reflect the views and policies of the Ministry of Environment and Energy, nor does mention of trade names or commercial products constitute endorsement or recommendation for use. The Ministry, however, encourages the distribution of information and strongly supports technology transfer and diffusion.

A HIGH INTENSITY ULTRAVIOLET LIGHT SOURCE AND DELIVERY SYSTEM FOR REMOTE STERILIZATION

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1.0) EXECUTIVE SUMMARY

The use of chemical oxidants, particulary chlorine, has been wide spread for control of zebra mussel infestations in both the United States and Canada. These treatments appear to have been very effective, however, there are several reasons why the search for alternate strategies continues. It follows that new control measures, should they be available, would focus on non chemical solutions or at least be useful in reducing chemical use.

An investigation of UV radiation was initiated by Aquatic Sciences Inc. in 1992 using standard "off the shelf" germicidal lamps and conventional technology. The results of this study had been very encouraging, however the ability to treat large volumes of water and penetrate significant distances remained an issue. In 1993, the University of Guelph, with significant input from Aquatic Sciences Inc. and Hutchins International Ltd., proposed a collaborative research venture to study a high intensity ultraviolet light source which used microwave technology as a potential means of overcoming these problems. The application to MOEE for research funding resulted in the current project.

This research project was originally planned as a testing and prototype development project over a period of two years. It has since been reduced to a one year duration with modified objectives which include (1) a "proof of concept" to establish the lethality of a high intensity ultraviolet light source in controlling zebra mussel populations in fresh water and (2) testing of a system capable of remote sub-aquatic delivery of lethal levels of ultraviolet radiation.

In pursuing the first of these objectives it soon became clear that the second objective was potentially redundant. This was mainly due to the unanticipated and remarkable extent to which the high intensity UV source penetrated even turbid water samples compared to conventional alternatives. Therefore, we immediately constructed flow through systems and initiated biological testing to determine the efficacy of the light source in a sterilization role.

Our "bench tests" have determined that the upper limit of volume flow rate at a depth of 25 cm at which high levels ($>80\%$) of instantaneous mortality were maintained is approximately 80 L/min. Beyond the scope of these trials was a full analysis of latent mortality and other sub-lethal effects which would certainly adversely influence the settling of zebra mussels down stream.

It is clear that the high intensity ultraviolet source is very effective in localized control of zebra mussel populations with few, if any, collateral environmental consequences. This makes it a very attractive alternative to chemical sterilization techniques in a wide range of applications. The results of our experimentation strongly support the recommendation that further development of this technology be pursued in the context of aquatic sterilization and industrial control of zebra mussels.

2.0) INTRODUCTION

Since their introduction to the Great Lakes in 1985/86, the proliferation of zebra mussels (*Dreissena polymorpha*) has proceeded at an alarming rate to the point where now much of the Great Lakes Basin as well as many inland lakes and the Mississippi River Basin have been affected (New York Sea Grant, 1994). Among the most critical and well publicized problems caused by the mussel is the gradual clogging of domestic, industrial and municipal water intake pipes.

The use of chemical oxidants, particulary chlorine, has been wide spread for control of zebra mussel infestations in industrial complexes in both the United States and Canada (Van Benschoten, *et al.* 1993) Treatments appear to have been very effective, however, there are several reasons why the search for alternate strategies continues. The production of chlorination byproducts such as trihalomethanes have been identified as potentially harmful from both an ecosystem and human health perspective. Environmental regulators including those at Ontario Ministry of Environment and Energy (MOEE), Environment Canada and Health Canada, have all given notice that the use of chlorine for these purposes is considered only a short term solution and that as new technologies are developed it's use will be phased out.

The use or development of other chemical control methodologies may result in a host of new handling, storage and ecological concerns and therefore it follows that new control measures, should they be available, would focus on non chemical solutions or at least be useful in reducing chemical use.

Current research initiatives along this vane include the study of acoustics, heat treatment, cathodic protection, filters, and non-toxic foul release coatings (Claudi, 1993).

The investigation of UV radiation was initiated by Aquatic Sciences Inc. in 1992 using standard "off the shelf" germicidal lamps and conventional technology. The results of this original study, also sponsored by MOEE (Lewis, 1993), had been very encouraging, however the ability to treat large volumes of water and penetrate significant distances in poor water quality remained an issue. In 1993, the University of Guelph, with significant input from Aquatic Sciences Inc. began research on a high intensity light source, which used microwave technology, as a potential means of overcoming these problems.

The main objective of the present research is to test a high intensity light source (Fusion Microwave VBL 3400) for its potential to produce the desirable quality and intensity of lethal ultraviolet radiation for control of zebra mussel larvae.

3.0) BACKGROUND

Recently completed research by Aquatic Sciences Inc. established effective wavelengths for control of the zebra mussel under a number of different test protocols. Work on small scale flow through systems from this proof of principle study helped to determine the mechanism by which zebra mussels of different ages can be controlled in the aquatic environment. Both shorter (UVC) and longer (UVB)

wavelengths were tested as well as combinations of both UVB and UVC.

The ability to penetrate greater distances in water was identified as an important asset to any technology which may be useful for zebra mussel control.

The technical limitations of delivering the appropriate quality and intensity of ultraviolet radiation is also the subject of other independent research proposals devoted to sterilization procedures in sealed environments. This work involved the University of Guelph (among others) in a proposal to develop a high intensity light source providing either photosynthetically active radiation (for plant growth) or ultraviolet radiation (for sterilization purposes). The latter application has coincidental technical objectives with those of the on going zebra mussel research under the direction of Aquatic Sciences Inc.

This mutual interest in applying the lethal properties of ultraviolet radiation to control micro-organisms or biofouling organisms has fostered the collaborative project herein described.

The focus of this project is the application of a high intensity light source (VBL 3400) for control of zebra mussel larvae. The VBL 3400 is an efficient microwave powered light source with the capacity to generate various intensities and spectra of light including UV wavelengths. It was anticipated that this technology would be useful for delivering appropriate lethal doses of ultraviolet radiation to remote (eg. subaquatic) sites for the purpose of causing mortality of existing organisms and limiting growth of various organisms including zebra mussels. The advantages of this technology appear to include its

energy efficiency, reliability, longevity and focusable point source which may allow better water penetration. In addition, by varying the lamp fill materials (which are proprietary), the spectral emission characteristics can be readily changed without modification to the lamp controller and power supply.

The implications are that ultraviolet disinfection may be useful for protection of small industrial water systems and with modifications could be useful in much larger systems. Other applications may include prevention of further introductions of exotic species through ballast water exchange of ocean going vessels.

4.0) METHODS

The project has been divided, to date, into four distinct phases: I - Lamp Procurement, II - Static Light Penetration Studies, III - Long Term Flow Through Studies, IV - High Flow Batch Tests.

Phase I involved procurement of the Fusion Microwave Lamp (VBL 3400) and appropriate bulb. This particular bulb (H-type) was chosen to produce wavelengths similar to those that had proven effective in on-going research by Aquatic Sciences Inc. The dominant wavelengths emitted from this bulb, similar to standard "medium pressure" bulbs, were the 365 nm and 254 nm, although a whole range of wavelengths are present between 200 and 400 nm.

Spectral radiance was measured through air using an Optikon 72 Spectrophotometer to determine the

baseline emissions of the test bulb prior to initiation of static tests.

Following procurement of the lamp and bulb, Phase II was initiated. This involved the fabrication of a test tank which would be used for preliminary static light penetration tests through varying water depths as well as flow through zebra mussel mortality determinations.

A schematic of this test tank design can be seen in Figure 1 and incorporates the ability to increase both depth and current which allowed maximum flexibility when determining the working capabilities of this lamp. The tank was also designed with a silica glass window in the chamber floor allowing researchers to measure light penetration through varying water depths. This not only allowed a determination of the appropriate protocols for flow through trials, but also a comparison with the already available "off the shelf" technology which was previously used in Aquatic Sciences Inc. on-going research. A baseline comparison of the standard medium pressure bulb used for preliminary work and the new bulb fitted for the VBL 3400 was also completed.

Static tests were carried out by measuring light penetration through various water depths (0 cm, 7.5 cm, 15 cm and 24.5 cm), using the spectrophotometer, on both the microwave and standard medium pressure lamps. Turbidity and water temperature were also recorded at various intervals during the study. Once the basic capabilities of the lamp were established, through these initial static tests, the initial parameters for flow through trials were established.

Phase III involved flow through tests to determine the zebra mussel control capabilities of the microwave lamp and medium pressure bulb under varying depth and flow conditions.

Based on the static tests, initial flow through trials involved pumping raw water, containing significant numbers of zebra mussel larvae from the Ontario Hydro Decew Hydro headworks located in St. Catharines, Ontario, through flow through exposure and control chambers. This water source had exhibited heavy infestation by adult zebra mussels and contained larval counts consistently above 10,000/m^3 throughout the summer months and in excess of 100,000/m^3 on several occasions.

In order to better control water quality and maintain consistent flow rates, two head tanks were used prior to water entering the contact chamber. Both the control and test chambers were identical to that used for static tests.

Initial trials involved flow rates of 10 L/min and a depth of 12.5 cm. The initial plan was to continue to increase depth and flow rate, as long as the lamp was successful in preventing downstream mussel settlement and survival.

At several week testing intervals, flow was increased to 20 L/min and 12.5 cm depth, 20 L and 25 cm depth and finally 30 L flow and 25 cm of water, which was the maximum flow capacity of the chamber. A parallel identical control system was in place during this aspect of the study. Both test and control flow through chambers were sampled for mortality of water borne veligers and settlement of pedi

veligers in downstream settling plates.

Twenty litre effluent water samples were collected and filtered through 53 μm nytex mesh net to concentrate the samples for analysis. Ten 1 ml sub samples were analyzed in sedwick rafter counting cells to determine age, numbers and mortality rates of both control and test organisms. General behaviour and condition of larvae were also noted.

The final phase of this project, completed in 1994, involved determination of the limits of the VBL 3400 in terms of its capability to treat higher flow rates for removal of water borne veligers and post veligers. The flow-through chamber was modified to increase its flow capacity and a larger submersible pumping system was put in place. Flow rates of up to 150 L/min were achievable through this system. Exposure experiments were performed under various water flow conditions through a single contact chamber. No parallel system was used for this aspect of the work. Instead tests were completed in either "light on" or "light off" mode.

Water flows of 40, 60, 80, 100 and 120 L/min through the UV exposure chamber at a depth of 25 cm were tested for effectiveness of achieving mussel larvae mortality. In order to ensure comparability between control and test data, samples were collected from the exposure chamber effluent in either "light on" or light off" mode. Test conditions were similar in all other ways.

Again, a 53 μm nytex mesh net was used to collect and concentrate the plankton from the effluent

stream. To ensure a relatively steady state, the system was maintained for 30 - 40 minutes at the set conditions, to ensure complete exchange of treated water prior to sample collection. A percent reduction of mussel larvae in chamber effluent due to the UV exposure was determined for each water flow as follows:

$$\% \text{ reduction} = \frac{\text{\# viable control larvae - \# viable test larvae}}{\text{\# viable control larvae}} \times 100\%$$

This equation accounts for both the observed dead larvae, as well as for the "unaccounted for" portion that did not exit the UV exposure chamber during test conditions.

Note that the different flow conditions were investigated on different days resulting in variable concentrations of mussel larvae in the water source for each test condition.

5.0) SAFETY

It is important to note that while the UV radiation studies were initiated because of its perceived environmentally friendly application, its near field impact is immediate and catastrophic. Safety precautions were extensive during all trials.

A purpose built trailer was put in place at the research site. All windows and doors were fitted with

automatic shut off alarms which could only be inactivated by UV research technicians. Technicians were well versed in handling UV installations. Exposed skin was covered and face shields were worn at all times when in the vicinity of the working lamp.

6.0) RESULTS AND DISCUSSION

6.1) Lamp Performance

In general, this version of the VBL 3400 lamp required a significant amount of trouble shooting and technician time. This was particularly true on start up. These problems make off-the-shelf use of the lamp for this purpose questionable. The spherical UV (type H) bulb used in this study is no longer being manufactured and so VBL 3400 lamps with UV capability may soon be in short supply. Presently, Fusion UV Curing Systems, a sister corporation of Fusion Lighting, have a number of lamp models which may prove to be useful for the zebra mussel control application. These longitudinal bulbs are focusable and also emit a highly intense beam of light.

The 3 KW, VBL 3400 lamp system exhibited significantly greater power than the system used for previous work which was 400 W. A comparison of the spectral radiance of each system can be seen in Figure 2. The penetration capability of the VBL 3400 "medium pressure" lamp system was excellent considering the distances through which this light was travelling and the added challenge of air/water interface (Figure 3). A comparison between the standard medium pressure unit used for preliminary work and the VBL 3400 show transmission differences at different water depths (Figure 4).

6.2) Biological Monitoring

Biological effectiveness was measured in three ways during the initial low flow trials.

The first was to measure the relative numbers of incoming mussel larvae that were removed from the water column as they passed through the exposure area. This number was a function of the relative number of veligers and post veligers, alive or dead, that were found in the downstream water sample in the test chamber as opposed to the control chamber.

The second was to measure the actual mortality rates of organisms that had not been removed from the water column and were found in the downstream water samples taken from both the control and test chambers.

Under all test conditions the percent removal was relatively high and in most cases was 70% or higher. This was particularly true of post veligers which must swim to maintain themselves in the water column, and tend to settled due to increased shell thickness if cilia are no longer functioning. It was apparent that a significant number of larvae were affected immediately upon exposure to the UV light.

Of the mussels that passed through the system and were found in the water column in the downstream settling chambers, mortalities were found to be 100% in test chamber in the majority of samples. Actual mortalities ranged from 70 - 100% in post veligers and 80 - 100% in veligers. Mortalities in controls

ranged from 2 - 40% (Figures 5 and 6). These mortality rates are comparable to the results of trials with other medium pressure UV lamps.

Finally samples were also collected from settling plates in the downstream settling chambers. Settlement was only observed in the control chambers (Table 1). While these numbers were low in all cases they provide further evidence of the effectiveness of UV control of zebra mussel settlement downstream of the zone of control.

Table 1: Downstream settlement rates for low flow trials; (max flow 30L/min @ 25 cm depth).

Location	Juvenile Density (/m^2)	
	Control	Test
Culture Plate	65	0
Outfall wall	21	0

In 1994, high flow tests revealed that significantly higher flows could be used with good results.

The observed numbers of viable veligers and post veligers in both the control and test samples are presented in Table 2. In addition, the percent reduction values for each water flow condition are listed in Table 2 and visually presented in Figure 7.

As expected, lower flows facilitated higher mussel larvae reduction values. Nearly complete elimination of veligers (99.5%) and post veligers (97.5%) was achieved at 40 L/min. Control effectiveness

decreased with increasing water velocity. A final value of 33.6% viable veliger reduction was achieved at 120 L/min. It appeared, from the data, as though adequate control could be attained with flows up to 80 L/min where approximately 80% of the larvae were removed.

A similar trend was observed in the post veliger data set where only a 14% reduction in viable larvae was attained at 120 L/min. In general the lower mortality can be attributed to increased shell thickness and pigmentation as larvae mature. The increased variability present in the post veliger data set can likely be attributed to the lower numbers present in the water source as well as the variable maturity rate of mussels in this age class which would in some cases be exhibiting shell thickening and the earliest signs of pigmentation.

It should be noted that these mortality figures represent instantaneous mortality upon exposure to the intense UV radiation. We can expect an additional component of latent mortality and sub-lethal effects which would vary inversely with flow rates. These longer term effects would ultimately be reflected by reduced settling of zebra mussels and extended influence of the ultraviolet radiation treatment.

Visually, the surviving larvae did not appear physically damaged at magnifications up to 40x. Visceral organs appeared intact and functioning. Stress was evident, however, based on reduced or absent cilia movement in of the UV exposed larvae when compared to the control larvae. Downstream settlement trials were not completed during these high flow trials. It would be interesting to investigate whether reductions in instantaneous mortality counts would translate directly to increased, long term survival and

growth of mussels on downstream substrates.

Table 2: Comparative effect of water flow on zebra mussel reduction using UV light

	Veliger			Post Veliger		
Condition L/Min	Total Viable # Control	Total Viable # Test	% Reduction	Total Viable # Control	Total Viable # Test	% Reduction
40	3493	16.5	**99.5**	331	8	**97.5**
60	3880	537	**86.2**	244	118	**51.6**
80	12182	2395	**80.3**	791	140	**82.4**
100	1105	434	**60.7**	220	106	**51.8**
120	3121	2072	**33.6**	166	143	**14.0**

7.0) CONCLUSIONS

The Fusion microwave lamp (VBL 3400) appears to be a highly potent light source which could prove to be readily adaptable for zebra mussel control under rigorous industrial conditions.

All indicators are that excellent zebra mussel control (i.e instantaneous mortality) was accomplished during the present. "proof of principle" study at flow rates up to 80 L/min and depths to 25 cm using a 3 kw light source.

Under lower flow conditions in fire protection make up water or other service water applications in industrial complexes, ultraviolet radiation sources could be engineered given the present state of knowledge to provide an effective non-chemical control method.

This technology may have applications in ballast water treatment of ocean going vessels for prevention of further exotic introductions using non-chemical means.

8) REFERENCES

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FIGURE 1: EXPOSURE CHAMBER

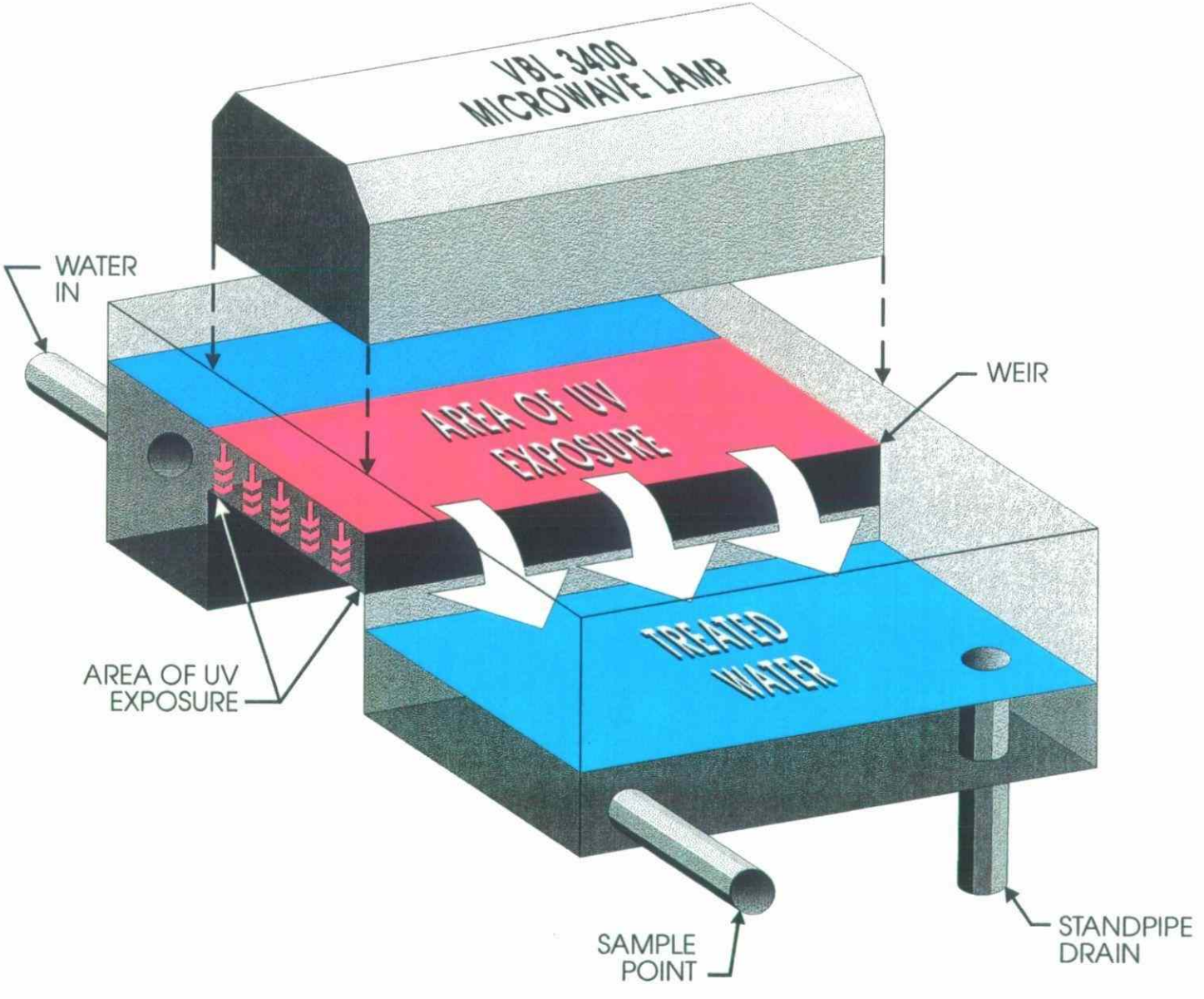

FIGURE 2: COMPARISON OF FUSION MICROWAVE and STANDARD MEDIUM PRESSURE SPECTRAL RADIANCE

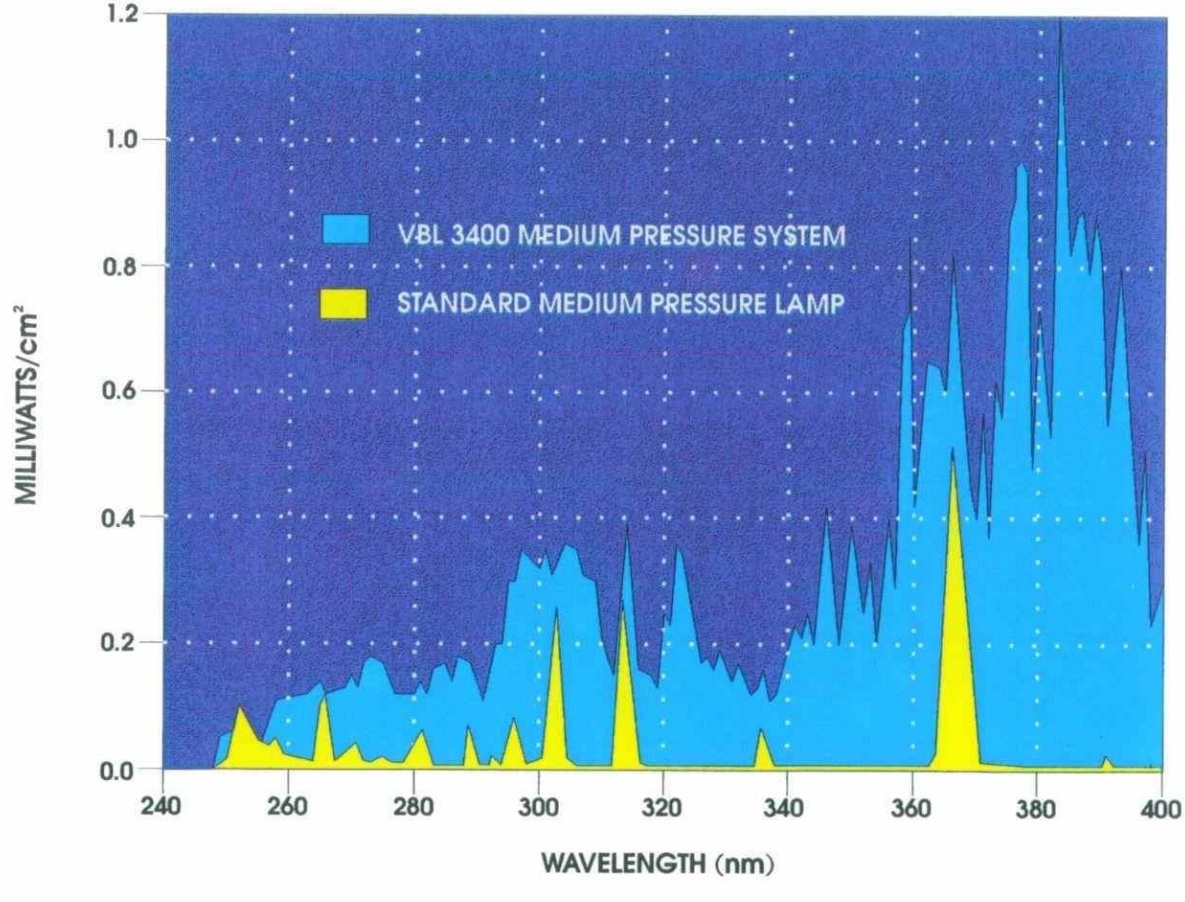

FIGURE 3: ATTENUATION OF UV WAVELENGTH THROUGH VARIOUS WATER DEPTHS

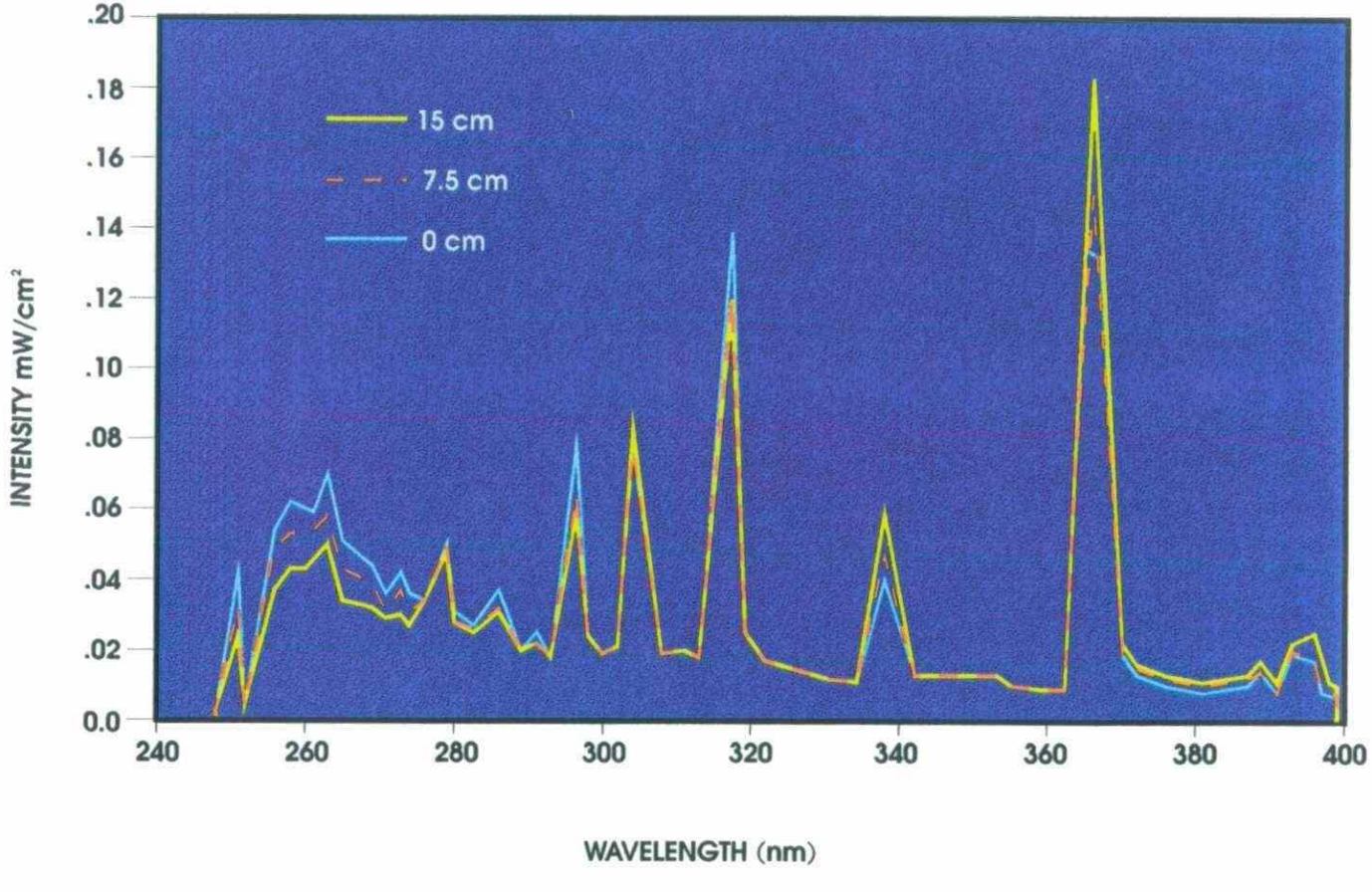

FIGURE 4: ULTRAVIOLET TRANSMISSION THROUGH WATER

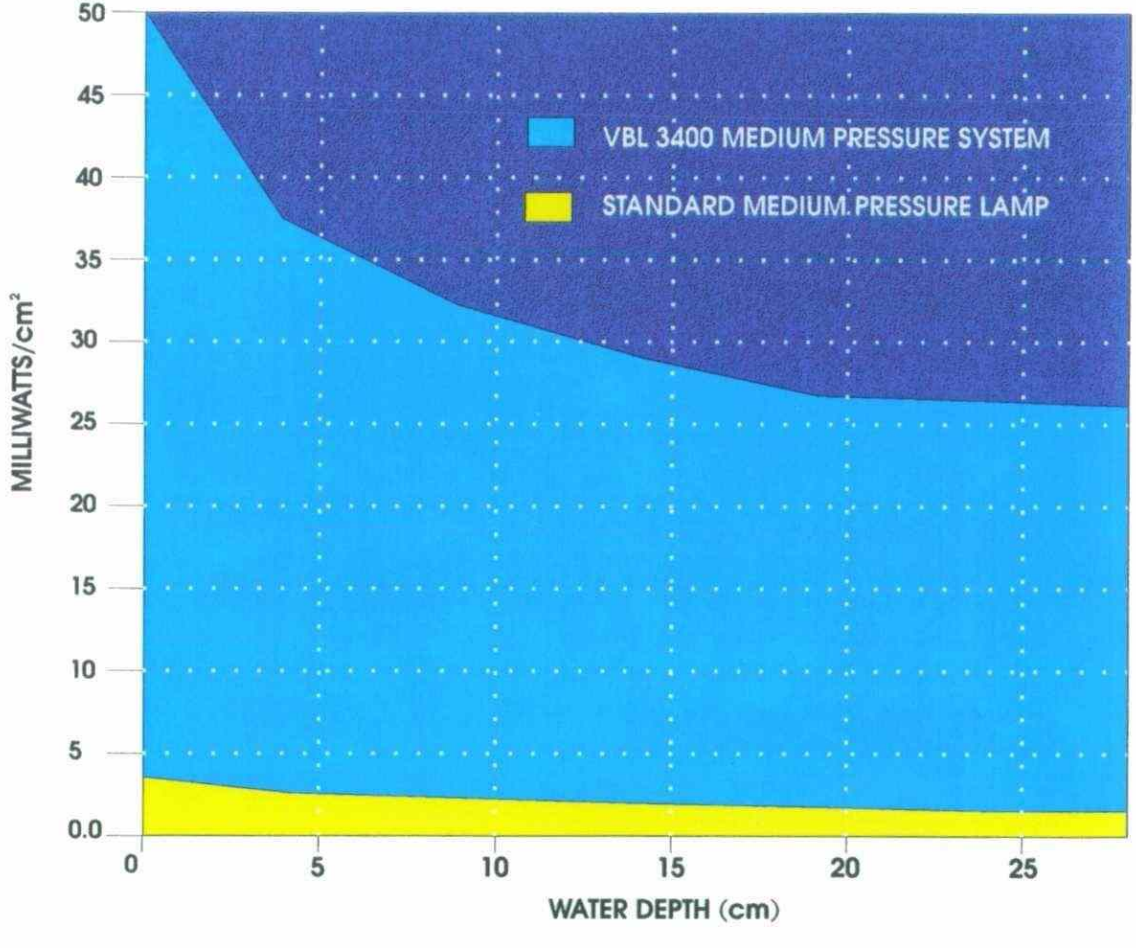

FIGURE 5: POST VELIGER TREATMENT
REDUCTION vs BACKGROUND MORTALITY

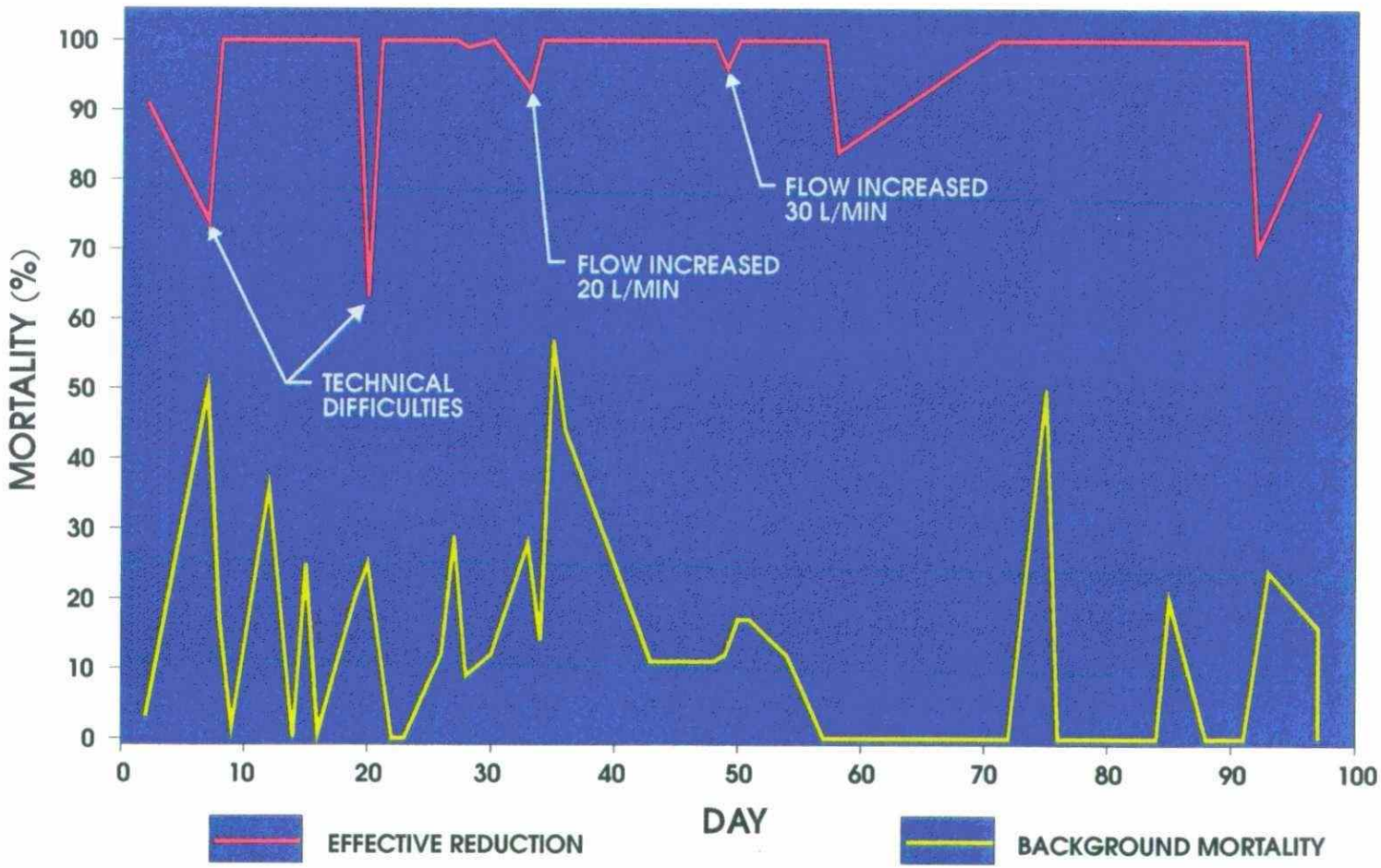

FIGURE 6: VELIGER TREATMENT
REDUCTION vs BACKGROUND MORTALITY

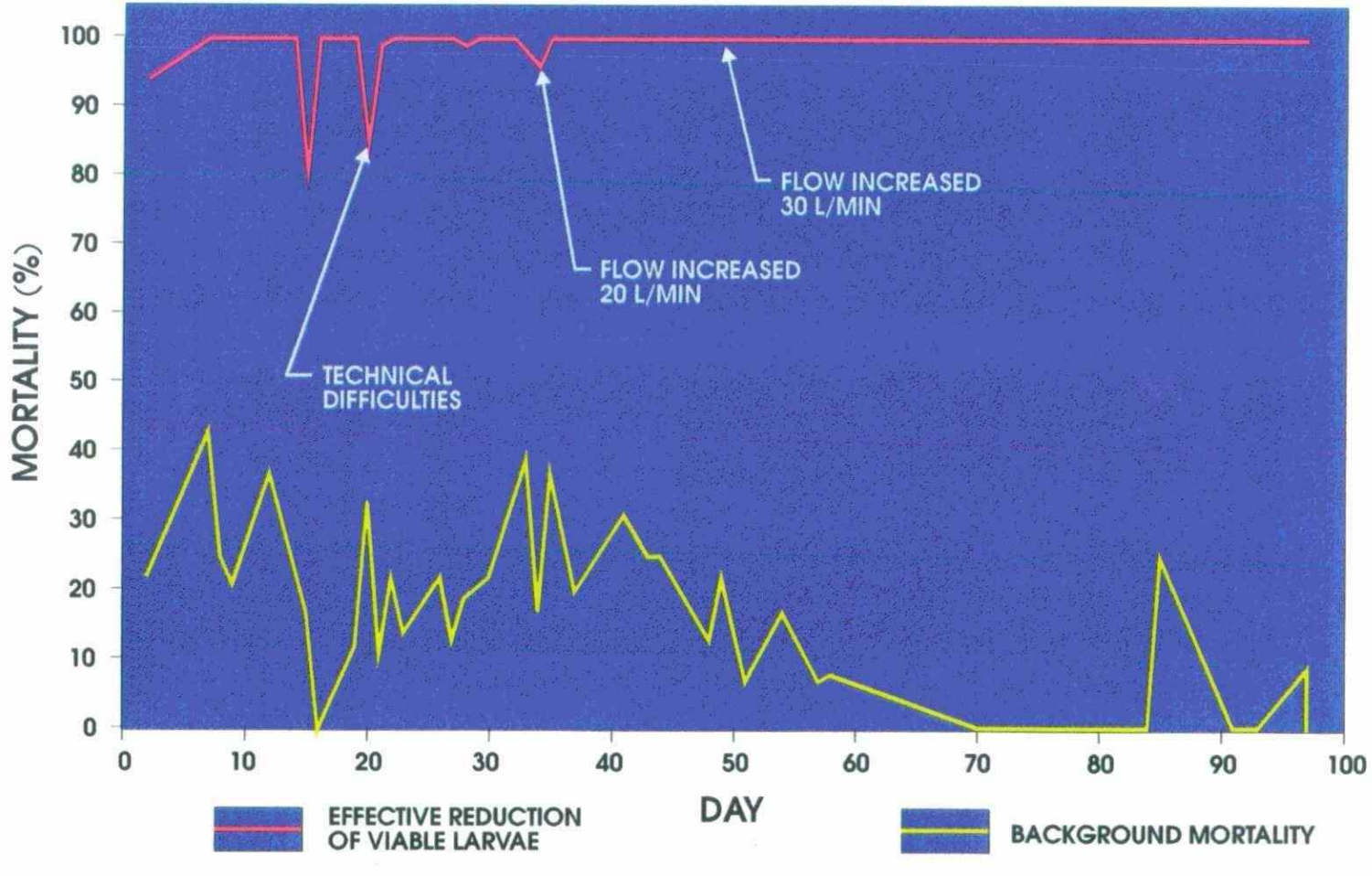

FIGURE 7: MICROWAVE LAMP
WATER FLOW vs LARVAE REDUCTION